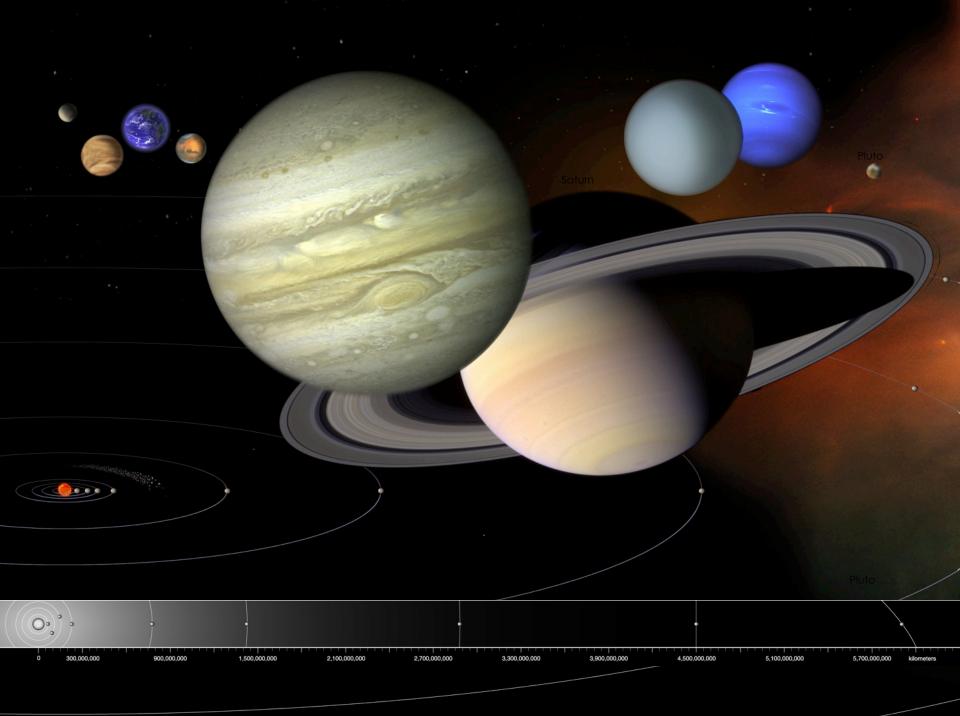


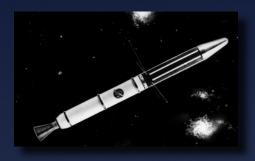
MEMORY TECHNOLOGIES IN SPACE: Radiation Hardened Magnetic Memories

Jean Y. M. Yang-Scharlotta Jet Propulsion Laboratory, California Institute of Technology, NASA

Outline

- > JPL and the Range of its Missions
- Data Storage in Past Space Missions
- Current Data Storage Memory for Space Applications
 - Power, Mass, Volume, & Reliability
 - Environment- Radiation
- Memory Needs for the Future
 - NASA-USAF study of future memory needs for space
 - Ideal Memory for Space Applications
 - Review of Radiation Hardened MRAM
 - STT-MRAM test results
- Summary

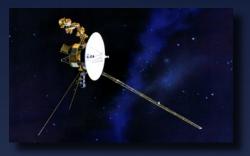




1st U.S. satellite Explorer 1 - Jan 28, 1958



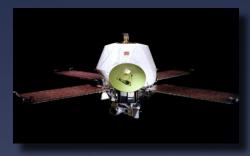
1st close-up images of another planet Mariner 4 to Mars - Nov 1964



1st fly-bys of Uranus and Neptune Voyager 2 - 1986 & 1989



1st U.S. spacecraft to the moon Ranger 7 - Jul 28, 1964



1st orbiter at another planet Mariner 9 to Mars - May 1971



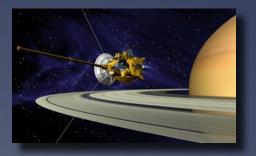
1st orbiter at Jupiter Galileo 1989-2003



1st planetary mission Mariner 2 to Venus – Aug 27, 1962

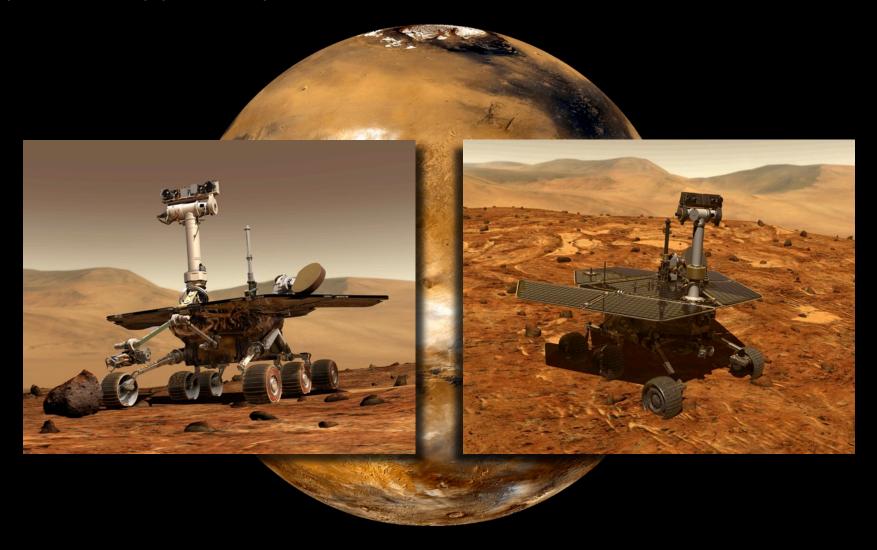


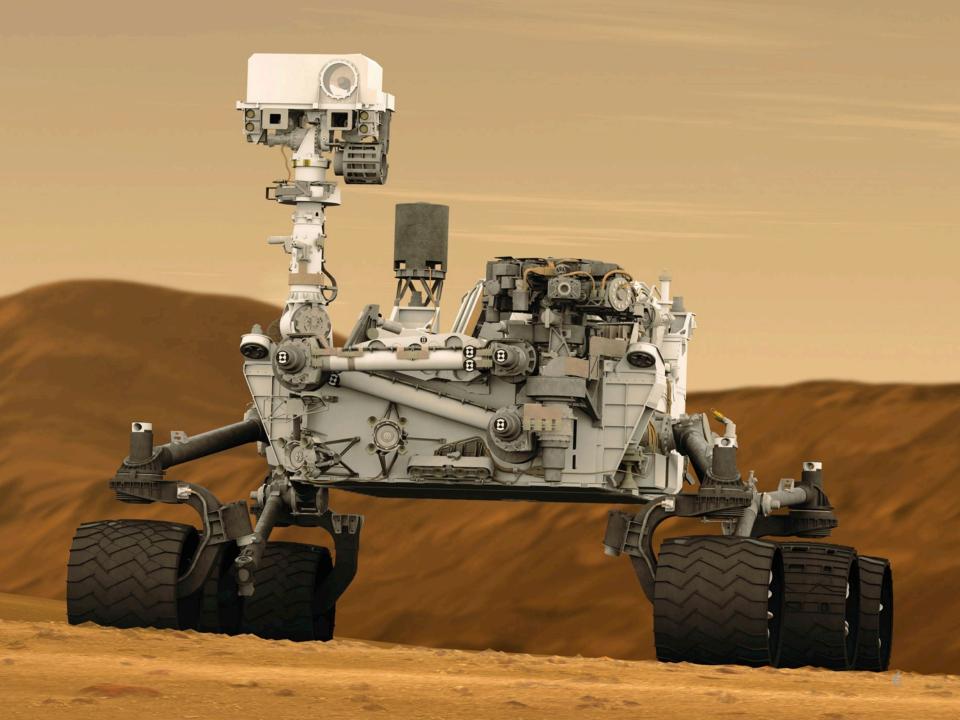
1st gravity assist mission Mariner 10 to Venus – Nov 7, 1973



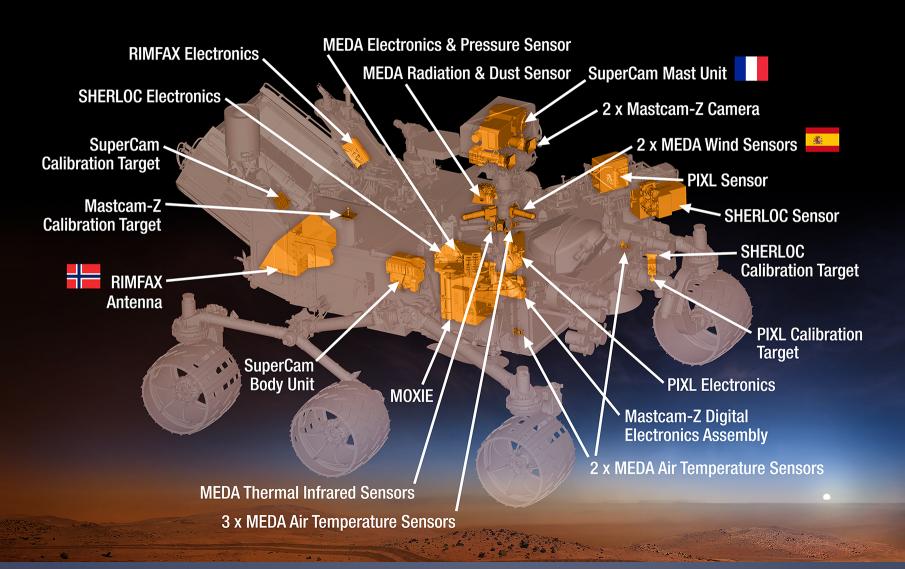
1st orbiter at Saturn Cassini October 15, 1997 -2017

Spirit and Opportunity landed in Mars in 2004



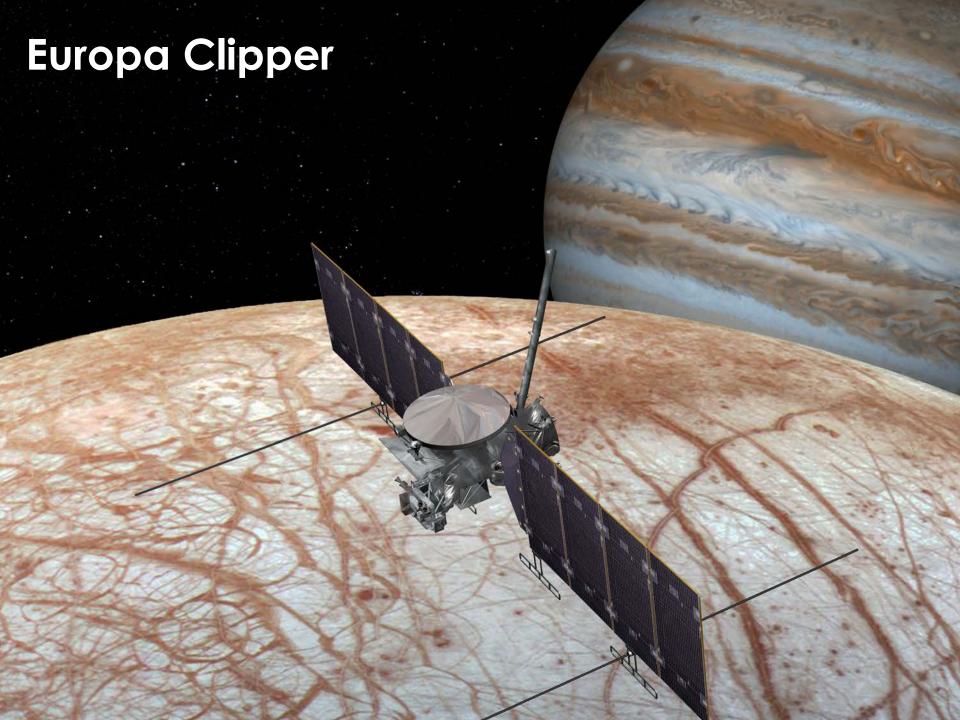


Mars 2020 Rover



Proposed Mars Helicopter





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Space Mission Data Storage



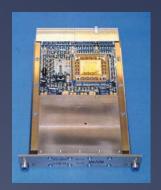
- Cassini (1997) was first NASA deep space mission to use Solid State Drive
- Previous missions, such as Galileo (1989) and Magellan (1989) used multi-track tape drives (almost 2 km of tape!)



Science data capacity can be a limiting factor in mission science & mission planning



- Many missions following Cassini, such as Mars Landers & Rovers, Stardust (comet dust sample & return), Genesis (deep space dust), JUNO (Jupiter) used data storage based upon a custom 2Gb Flash data card – using devices no longer manufactured
- New Laser-Optical links will allow orders of magnitude greater communication bandwidth requiring <u>TB levels</u> of onboard data storage



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12 Mary 2015

NAND Flash- Current NVM for Space

- Significant increase in density and capacity over the last
 15 years, driven by the mobile and storage market
- Now the process technology node driver in the semiconductor industry
- Introduction of new technologies driving density even higher
 - Multi Level Cell (MLC)
 - Triple Level Cell (TLC)
 - On-board Error Correction (ECC)
 - 3D-NAND
- Can we use NAND to bring TB data storage to space?

Spacecraft Systems Considerations: <u>P M V E R</u>

Power is a Limiting Factor in Space Apps

- Three sources of power in spacecraft & satellites
 - Battery
 - Solar
 - Nuclear (radio-isotope)

Mass and Volume

- The cost of launch depends upon the Mass and Trajectory Required
- The Minotaur–C shown here can launch 1450 kg into LEO for ~\$6.2K/kg

Reliability

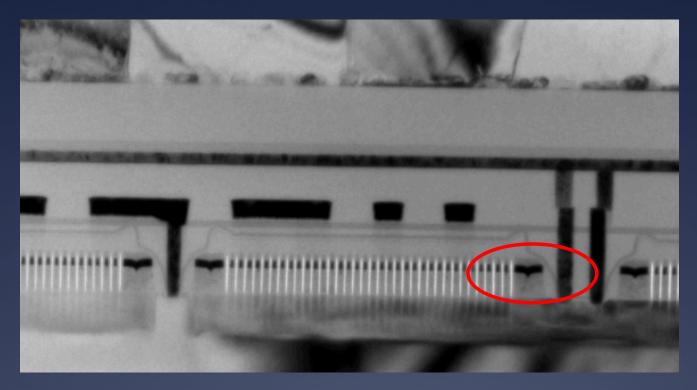
- Mitigations and Management Exist
 - Upscreening
 - Error Correction/ Redundancy





Source: www.orbital.com/SpaceLaunch/Minota ur/IV/

Advanced 19nm Planer NAND



- Example 19nm NAND strings show 32 physical memory cells between two select transistors.
- Note select transistor size (~200nm) does not scale and is limited by high voltages required for program/erase (up to 20V)

NAND Flash for Space P M V E R

Environment- Radiation



- Radiation sources are varied and widespread
 - Solar wind, gamma bursts, event horizons, on-board radioistopic generators
 - Magnetic lines of force– entrapment of energetic particles





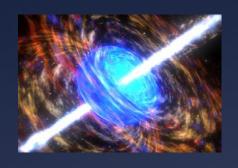
Space Radiation Challenges Radiation dose per year

- Earth
 - LEO (ISS Shuttle)
 - o MEO
 - GEO (GOES)

- ~ 100rad
- ~ 100krad
- ~ 1krad

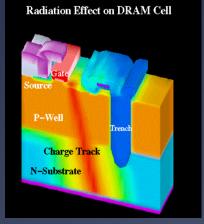
- > Mars
 - Surface ~ 2krad
 - Orbit ~ 5krad
- Jupiter
 - Transfer ~ 100Mrad

Effects of Radiation

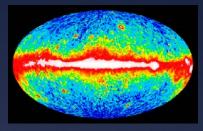


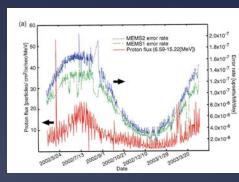
- Gamma Radiation capture of photons at defect sites
 - Increases leakage, alters voltage threshold





- Neutron radiation May cause destruction or permanent alteration of crystalline structure
 - Upsetting device parameters and operation

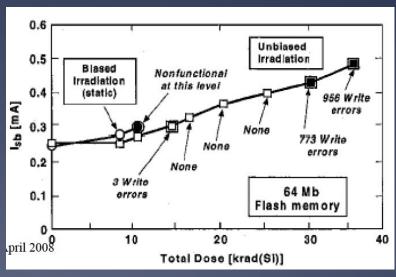




NAND Total Dose Capability

- For all products > 32 Mb the CHARGE PUMP is the most susceptible to radiation damage
 - 90% attributable to high voltages generated and stress upon cascade capacitors
- These Issues manifest themselves in write and erase errors which can occur at doses as low as 10 KRad(Si)





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NASA-USAF Memory Study

FY17 study indicated a need exist for rad-hard, high performance, high density memory to support next generation space-based systems

Time	Memory Type	Capacity (mean)	Capacity (mean + σ)	Data Rate (mean)	Data Rate (mean + σ)	Radiation (mean)	Radiation (mean + σ)
5 Years	NVM	62.2 GB	202 GB	0.125 Gbps	0.125 Gbps	75 kRad	150 kRad
10 Years	NVM	1.0 TB	2.1 TB	1.1 Gbps	1.9 Gbps	152 kRad	337 kRad
15 Years	NVM	5.7 TB	13 TB	34 Gbps	56 Gbps	167 kRad	261 kRad

Time	Memory Type	Capacity (mean)	Capacity (mean + σ)	Data Rate (mean)	Data Rate (mean + σ)	Radiation (mean)	Radiation (mean + σ)
5 Years	VM	0.52 GB	0.98 GB	0.1 Gbps	0.1 Gbps	83 kRad	162 kRad
10 Years	VM	1.8 GB	3.8 GB	6.8 Gbps	13 Gbps	147 kRad	351 kRad
15 Years	WV	51 GB	91 GB	24 Gbps	37 Gbps	230 kRad	416 kRad

Ideal Memory Technology for Space

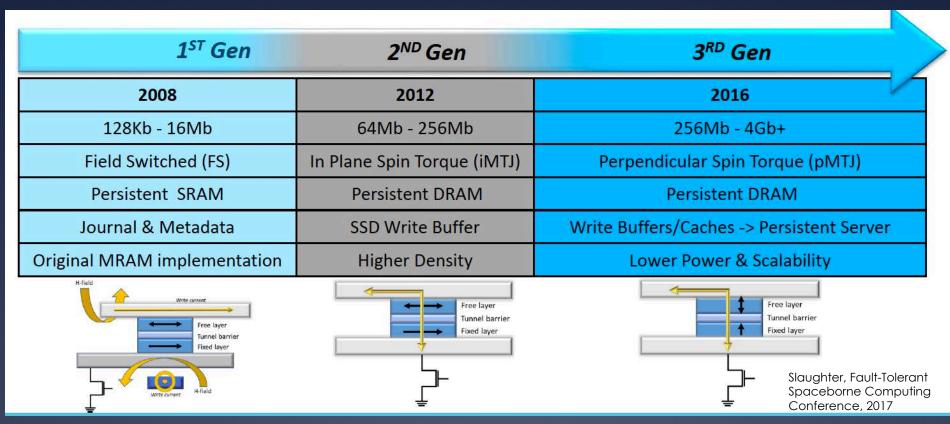
- Good radiation tolerance
- High reliability
- In addition to characteristics also desired by commercial applications:
 - High density
 - Fast Operations
 - High endurance
 - Good retention
 - Low power consumption
- Are there Emerging Memories out there that may satisfy some of the requirements?

Emerging Memory Candidates

Memory Trends Emerging							
Technology	Technology Density Rad hard? Follow-Up Recommendation		Recommendations				
Magnetic RAM (MRAM)/Spin- Torque Transfer MRAM (STT- MRAM)	16Mb-256Mb	Yes	Test	We recommend testing of STT-MRAM parts and working with vendors to explore development products			
Phase Change RAM (PCRAM)	2Mb - 5Gb	Yes	watch	We recommend continued tracking of industry developments to see if solutions to known problems emerge			
Conductive Bridge Memory	512kb	Yes	watch	We recommend continued monitoring of this technology until density scales to Gb range			
Reduction- oxidation-based resistive memory (ReRAM)	512kb - 4Mb	Yes	watch	Strong candidates for rad hard non-volatile memory if density scales to Gb. We recommend continuing to track and test components as they become available.			

MRAM seems to be a mature candidate from emerging memories with good density and heritage

Magnetic Memory

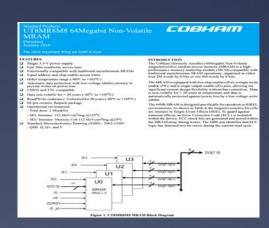


MRAM density progression has increased in the last few years with introduction of spin torque MRAMs

Radiation Hardened MRAMS

- 1st Gen Toggle MRAM is an established technology with multiple commercial vendors
- 16Mb radiation hardened chips available from Honeywell and Cobham-successfully combining radiation harden support circuitry with MRAM





Value-add suppliers such as e2V and 3Dplus also offer screening

Rad Hard MRAM

- Example Datasheet Specification Demonstrating Baseline Capability
 - -Total dose: 1 Mrad(Si)
 - SEL Immune: 112 MeV-cm2/mg
 - SEU Immune: Memory Cell 112 MeV-cm2 /mg

Rad Hard MRAM –Total Ionizing Dose and Heavy Ion Tolerance

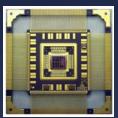
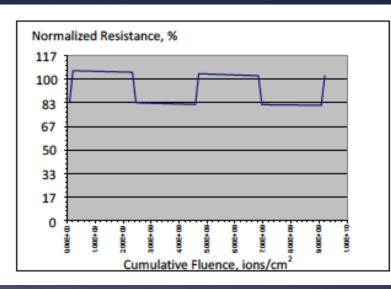


TABLE I

TID DATA, PRIOR TO IRRADIATION AND AFTER IRRADIATION AT 50, 100, 300, 500, AND/OR 1000 KRADS, FOR TEST PARAMETERS IN A 1 MBIT MRAM

Parameter metric	Values Normalized to Pre-Irradiation Values, %				
Radiation level	50 krad	100 krad	300 krad	500 krad	1000 krad
Read reference voltage (Co60)	100.1	100.2	100.4	100.5	100.7
Write reference current (Co60)	100.3	100.5	101.0	101.2	101.9
Read cycle time (Co60)	100.0	100.0	100.0	100.0	100.0
Write cycle time (Co60)	100.0	100.0	100.0	100.0	100.0
Pattern test counts (Co60)	100.0	100.0	100.0	100.0	100.0
Read reference voltage (Aracor)	100.1	100.2	100.3	No data	100.6
Write reference current (Aracor)	99.8	99.9	99.9	No data	100.0
Read cycle time (Aracor)	100.0	99.8	99.6	No data	99.3



R. R. Katti et al., *IEEE Radiat. Eff. Data Work.*, pp. 103–105, 2009.

Rad Hard MRAM -Heavy Ion Tolerance

TABLE III SEU RESULTS

						Eff. LET		
	Bias		V_{DD}		Angle	(MeV-	Eff. Fluence	
SN	State	Temp	(V)	Ion	(°)	cm ² /mg)	(ions/cm ²)	Upsets
22	Static	room	3	Xe	60	112	1.0x10 ⁷	0
19	Static	room	3	Xe	60	112	$1.0x10^{7}$	0
17	Static	room	3	Xe	60	112	$1.0x10^{7}$	0
16	Static	room	3	Xe	60	112	$1.0x10^{7}$	0
22	Unpowered	room	0	Xe	60	112	$1.0x10^{7}$	0
19	Unpowered	room	0	Xe	60	112	$1.0x10^{7}$	0
17	Unpowered	room	0	Xe	60	112	$1.0x10^{7}$	0
16	Unpowered	room	0	Xe	60	112	1.0x10 ⁷	0

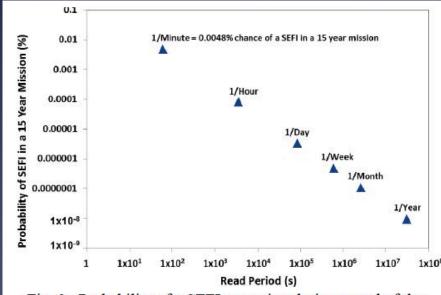


Fig. 3. Probability of a SEFI occurring during a read of the UT8MR8M8 64 Mbit device versus read frequencies.

C. Hafer et al. IEEE Radiat. Eff. Data Work., 2012.

No single bit errors at up to 112 LET and 1e7 ion fluence

Rad Hard MRAM Neutron and Alpha Particle Tolerance

TABLE I
NEUTRON FLUENCE DURING 8H OF EXPERIMENTS

Energy (MeV)	Fluence of high energy peak (n/cm ²)	Fluence of the lower neutron energies down to 1MeV (n/cm ²)		
25	7.55E+08	11.4E+08		
50	1.53E+09	2.6E+09		
80	4.46E+09	6.78E+09		

TABLE II							
ALPHA PARTICLE FLUENCE DURING EXPERIMENTS							

Test Type	Hours o	f exposure	Fluence (He ²⁺ /cm ²)		
	Closed	Decapped	Closed	Decapped	
Static	24	32	5.7E+08	7.7E+08	
Dynamic Stress	32.5	24	7.8E+08	5.7E+08	
March C-	54	12	13E+08	2.8E+08	
MATS+	34	12	8.2E+08	2.8E+08	

G. Tsiligiannis et al., *IEEE Trans. Nucl. Sci.*, vol. 60, no. 4, pp. 2617–2622, 2013.

No single event upsets during static and dynamic modes

STT-MRAM Radiation Results

>STT-MRAM tests

- Demonstrated that the STT MRAM achieves significant TID tolerance (> 1 Mrad [Si])
- For heavy ion testing, no data lost was seen when tested unbiased up to > 2 x 10⁷/cm² with a LET of 33.7 MeV-cm2/mg
- Achieved significant hardness, with caveat that when biased SEFIs can pose problems

Ion	Energy	LET	Fluence	Bit Errors
Ne	25 Mev/amu	1.9 MeV-cm2/mg	2.00E+07	0
Ar	25	7.6	2.00E+07	0
Kr	25	33.7	2.00E+07	0

Summary

- The challenges facing engineers for space missions are many and sometimes contradictory
- On-board data storage is critical to space missions and future missions will require significantly more capacity
- Memory Technologies must be Dense, Radiation Tolerant, and Reliable
- MRAM is a candidate for future memory to support space application supported by higher density enabled by the new STT architecture, initial radiation test results, and radiation hardened MRAM heritage

Acknowledgments

- Advanced Memory Study is a NASA-wide study in collaboration with USAF to examine the need and the path to support the need for radiation tolerant memory devices for space-based systems.
- Raphael Some, Karl Strauss, and Steven Guertin for their technical and programmatic contributions
- We acknowledges the generous support of the California Institute of Technology and the National Aeronautical and Space Administration
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Appendix